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Short-living supermassive magnetar model for the early X-ray flares following short GRBs

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Abstract We suggest a short-living supermassive magnetar model to account for the X-ray flares following short $\gamma-$ray bursts. In this model, the central engine of the short $\gamma-$ray bursts is a supermassive millisecond magnetar, that is formed in double neutron stars coalescence. The X-ray flares are powered by the dipole radiation of the magnetar. When the magnetar has lost a significant part of its angular momentum, it collapses to a black hole and the X-ray flares disappear abruptly.

Key words: Gamma Rays: bursts—radiation mechanisms: nonthermal—magnetic fields—stars:neutron—stars: rotation

1 INTRODUCTION

So far, the X-ray flares following short GRBs have been detected in GRB 050709 and in GRB 050724 (Villasenor et al. 2005; Barthelmy et al. 2005). In GRB 050709, a short GRB localized by HETE-II, X-ray flares occurred ~ 10 s and ~ 16 days after the GRB (Fox et al. 2005). The details of the flares are unclear owing to the rare data. Much better X-ray flare data is available for GRB 050724, a short GRB localized by *Swift*. The data has been summarized in Barthelmy et al. (2005; see also Zhang et al. 2006). The X-ray telescope (XRT) observation starts at ~ 79 s after the trigger. An extended flare-like epoch stops at ~ 200s after which the lightcurve decays rapidly (with a temporal slope

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index ~ -10). A second, less energetic flare epoch peaks at ~ 300 s, which is followed by another steep decay with a slope ~ -7. In this work, we call the first and the second flare epochs as the "early X-ray flares". A third, significant flare epoch starts at $\sim 2 \times 10^4$ s, and the decay slope after the peak is ~ -2.8. We call the third one as the "late X-ray flare".

The X-ray flares following short GRBs, like those detected in the long GRB X-ray afterglows, may indicate the long activity of the central engine (e.g., Barthelmy et al. 2005; cf. MacFadyen et al. 2006). But the actual mechanism for the long activity of the short GRB central engine is still unclear (Proga & Zhang 2006; Perna et al. 2006; Dermer & Atoyan 2006). The difficult is that in the double neutron stars coalescence scenario (i.e., the leading model of the short GRBs; e.g., Eichler et al. 1989), the typical energy input episode is just in order of the duration of the short burst, provided that after the merger a black hole is formed (e.g., Rosswog & Davis 2002; Lee et al. 2004).

In this work, we suggest that the X-ray flares following short GRBs could be understood if after the two neutron stars merger, a millisecond rotating magnetized supermassive neutron star (SMNS) instead a black hole, is formed.

2 THE MODEL

After the merger of two neutron stars, a supermassive neutron star (SMNS) with a mass $\sim 2.5\ M_{\odot}$, differentially rotating with a period of $P \sim 1$ ms, can be formed (e.g., Kluźnik & Ruderman 1998; Rossowog & Davis 2002). The maximum stable mass of a slowly rotating neutron star is $1.8 - 2.3\ M_{\odot}$ (Akmal et al. 1998), and the uniform rotation could increase these values by at most $\sim 20\%$ (e.g. Cook et al. 1992, 1994, and references therein). The SMNS therefore could survive before it has lost a significant part of the angular momentum, if the state equation of the nuclear material is stiff enough (cf. Shibata et al. 2006).

Though B_o, the initial surface magnetic field of the nascent SMNS, may be just in order of 10^{12} G or lower[1], much higher surface dipole magnetic field B_{dip} may be generated by several dynamo actions in a very short time. (i) Currently, the Rossby number $R_o \leq 1$ (Rosswog, Ramirez-ruiz & Davis 2003), both the α^2 and the $\alpha - \Omega$ dynamos could amplify the initial field effectively and $B_{dip} \sim 10^{15}$ G is expected (Duncan & Thompson 1992; Thompson & Duncan 1993). (ii) The convective dynamo can also

[1] After the submission of this work, several relevant papers appeared. Dai et al. (2006) proposed a post-merger millisecond differential rotating neutron star model to account for the X-ray flares following short GRBs. Price & Rosswog (2006) found out that in their MHD simulation of the double neutron star coalescence, a magnetar might be formed. Fan & Xu (2006) suggested that the long term X-ray flat segment detected in short GRB 051221A could be well accounted for, provided that the central engine was a magnetar. These last two findings are consistent with our model.

generate a very strong dipole filed (Duncan & Thompson 1992). (iii) If soon after the sudden formation of the SMNS, the convective and hydrodynamical instabilities have been greatly diminished. The magnetic field could be amplified by the linear amplification process (Kluźnik & Ruderman 1998) and $B_{dip} \sim 10^{15}$ G or stronger is still expected in a timescale $\sim 10\ B_{o,12}^{-1} P_0$ seconds (Spruit 1999). Here and throughout this text, the convention $Q_x = Q/10^x$ has been adopted in cgs units.

When the surface magnetic field strength reaches $\geq 10^{15}$ G, the differential rotation will be terminated in a very short timescale by the magnetic braking (e.g., Shapiro 2000; Shibata et al. 2006)

$$\tau \sim 10^2 (\frac{B_{dip}}{10^{15} G})^{-1} (\frac{R_s}{15 \text{ km}})^{-1/2} (\frac{M_s}{2.5 M_\odot})^{1/2} \text{ ms}, \tag{1}$$

where R_s and M_s are the radius and mass of the differentially rotating SMNS, respectively. That means the differentially rotating SMNS is estimated to evolve to a uniform rotation profile on a timescale much shorter than the spindown time of a uniformly rotating star(Eq. [3], derived below). So the SMNS is mainly supported by the rapid uniform rotation rather than the differential rotation.

The millisecond magnetar will lost their angular momentum quickly through the dipole radiation and strong Poynting flux dominated outflow is ejected. As a significant part of its angular momentum has been lost, the SMNS is very likely to collapse to a black hole. Before that time, the magnetic dissipation of the Poynting flux dominated outflow may be able to power detectable X-ray flares, which is of our interest. The dipole radiation luminosity is (e.g., Usov 1994)

$$L \sim 3 \times 10^{50} \text{ ergs s}^{-1}\ B_{dip,15}^2 R_{s,6}^6 \Omega_4^4, \tag{2}$$

where Ω is the angular velocity.

The corresponding spin-down timescale is

$$t_{sd} \sim 4 \times 10^2 \text{ s } \frac{j_s}{0.6} (\frac{M_s}{2.5 M_\odot})^2 (\frac{R_s}{15 \text{ km}})^{-6} \Omega_4^{-4} B_{dip,15}^{-2}, \tag{3}$$

where j_s is the specific angular momentum. In this Letter we focus on the case of the SMNS spinning down exclusively via a magnetospheric wind, but it is also possible that significant spindown can also occur through gravitational wave emission, such as those driven by r-mode instabilities(Andersson 1998). A rough estimation of this timescale is within a year (Vietri & Stella 1998), much longer than the timescale through magnetic dipole radiation. On the other hand, many aspects of the present theoretical calculations regarding gravitational waves are uncertain(Fryer and Woosley 2001). So in our Letter we just take into account the electromagnetic spindown.

In the Poynting-flux dominated outflow, the X-ray flare emission could be due to the dissipation of the magnetic field (Usov 1994; Thompson 1994) or internal shocks with magnetization (Fan et al. 2004). For illustration, here we take the global MHD condition

breakdown model to calculate the emission. By comparing with the pair density ($\propto r^{-2}$, r is the radial distance from the central source) and the density required for co-rotation ($\propto r^{-1}$ beyond the light cylinder of the compact object), one can estimate the radius at which the MHD condition breaks down, which reads (Usov 1994; Zhang & Mészáros 2002)

$$r_{MHD} \sim 2 \times 10^{16} L_{50}^{1/2} \sigma_1^{-1} t_{v,m_{-3}} \Gamma_2^{-1} \text{ cm}, \tag{4}$$

where σ is the ratio of the magnetic energy flux to the particle energy flux, Γ is the bulk Lorentz factor of the outflow, $t_{v,m}$ is the minimum variability timescale of the central engine. Beyond this radius, intense electromagnetic waves are generated and outflowing particles are accelerated (e.g. Usov 1994). Such a significant magnetic dissipation process converts the electromagnetic energy into radiation. The radiation should be delayed in a timescale (relative to the initial hard $\gamma-$ray spike)

$$\tau_{delay} \sim \frac{r_{MHD}}{2\Gamma^2 c} = 33 \text{ s } L_{50}^{1/2} \sigma_1^{-1} t_{v,m_{-3}} \Gamma_2^{-3} \text{ cm}, \tag{5}$$

which matches the observation of GRB 050709 and GRB 050724.

At r_{MHD}, the corresponding synchrotron radiation frequency can be estimated as (Fan et al. 2005)

$$\nu_{m,MHD} \sim 6 \times 10^{16} \sigma_1^3 C_p^2 \Gamma_2 t_{v,m_{-3}} (1+z)^{-1} \text{ Hz}, \tag{6}$$

where $C_p \equiv (\frac{\epsilon_e}{0.5})[\frac{13(p-2)}{3(p-1)}]$, ϵ_e is the fraction of the dissipated comoving magnetic field energy converted to to the comoving kinetic energy of the electrons, and the accelerated electrons distribute as a single power-law $dn/d\gamma_e \propto \gamma_e^{-p}$. So most energy is radiated in the soft X-ray band.

For the magnetic-dominated e^+e^- plasma, the diamagnetic relativistic pulse accelerator (DRPA) mechanism can convert most of the initial magnetic energy into the ultrarelativistic energy of a fraction of the surface particles. In the numerical simulation of such a plasma, Liang & Nishimura (2004) discovered that the plasma pulse bifurcated repeatedly, leading to a complex, multipeak structure at late times. *So the flares from the magnetic dissipation can show repeated, multiple structures.* Alternatively, the multiple flares may suggest that the magnetic dissipation takes place just locally rather than globally. The emission from different dissipation region arrives at different time and thus gives rise to multiple flares (Giannios 2006).

Our model is based on the double neutron stars merger model for short gamma-ray bursts (e.g. Eichler et al. 1989), which seems to be supported by the current host galaxy and afterglow observations (Barthelmy et al. 2005; Fox et al. 2005; Gehrels et al. 2005). The double neutron stars merger model is also consistent with the rate and the luminosity function of short GRBs detected by HETE-2/*Swift* (Piran & Guetta 2006, and the references therein). The neutron star-black hole merger model is an important

alterative. But in the black hole and neutron star merger scenario, it is very hard to produce the X-ray flares. *Therefore, if X-ray flares following a short GRB have been detected and the short GRB is found to be outside of the galaxy, the double neutron star merger model is strongly supported (Note that just double neutron star and black hole-neutron star merger can occur outside of the host galaxy, see Fryer et al. [1999] for details).* The X-ray flares then could play an additional role. When the double neutron star merger occurring outside of their host galaxy, the X-ray afterglow emission seems to be very weak and may be undetectable for the XRT in a long term, as in the case of GRB 050709 (Gehrels et al. 2005). However, the energetic X-ray flares provide us the chance to get a much better location.

3 DISCUSSION

Swift XRT has revealed a new, rich, and unexpected phenomenology of early X-ray afterglows observations. The most important one may be the energetic flares observed hundreds to thousands of seconds after the initial burst signal in both long and short GRBs (e.g. Burrows et al. 2005; Barthelmy et al. 2005). All these X-ray flares can be well interpreted by the "inner energy dissipation model", for example, the late internal shock model (Fan & Wei 2005; Zhang et al. 2006) and/or the late magnetic energy dissipation model (Fan et al. 2005). In this model, the long activity of the central engine is needed. However, a proper model for the long activity of the short GRB is still unavailable.

In this Letter, we suggest a magnetized central engine model for the X-ray flares in short GRBs. We take the popular two neutron stars coalescence model (e.g., Eichler et al. 1989) but to assume that after the merger, a differential rotating neutron star rather than a black hole, is formed. Soon after its sudden formation, the initial magnetic field has been amplified significantly by several possible dynamos (e.g., Duncan & Thompson 1992; Thompson & Duncan 1993; Kluźniak & Ruderman 1998; Spruit 1999), and the dipole magnetic field could be as strong as $\sim 10^{15}$ G. The differential rotation of the SMNS has been terminated by the magnetic braking. The early X-ray flares are powered by the dipole radiation of the nascent neutron star. They turn off when the supermassive neutron star collapses to a black hole. If this scenario is correct, X-ray flares much more energetic than that detected in GRB 050724 may be detectable in the coming months and years by *Swift*. The other speculation is that some short GRBs with X-ray flares would occur outside of their host galaxies.

The outflow powering the X-ray flares are Poynting-flux dominated, so the emission should be linearly polarized, as suggested by Fan et al. (2005). In this model, no strong MeV-GeV photons accompanying the X-ray flare (due to the synchrotron self inverse Compoton effect) are expected, in contrast to the baryon-rich internal shock model (see Wei et al. 2006 for a primary suggestion).

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